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An Experimental Study of Atmospheric Optical Transmission

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This paper reports measurements made on a 23-mile, experimental, atmospheric, optical-transmission link for possible use as a standby substitute for microwave radio when the radio suffers severe multipath or obstruction fading. To allow comparison of transmission on a microwave and on an optical path, we used two parallel systems. One, a microwave system at 11 GHz, allowed frequency-selective fading to be measured, and the other, an optical system at 6328Å, allowed amplitude changes of the received optical signal to be obtained. The measured clear-air loss on the optical path is 27 dB. This measurement is made up of 17 dB of atmospheric scattering and 10 dB due to the receiving antennas intercepting only 10 percent of the beam at the receiver. The signal-to-noise ratio, calculated using measured background sky-noise and measured received power, is about 60 dB for a 100-MHz band. The beam diameter was measured to be 32 feet where the signal is down 20 dB. On the single occasion when frequency-selective microwave fading was observed, there was no fading of the optical signal. We find that it is necessary to control the transmitter elevation angle with a servo error signal from the receiver; the azimuth angle needs only occasional manual correction. The optical beam can be automatically reacquired after severe atmospheric attenuation, and that scintillation is usually several decibels, and occasionally as much as 10 dB.

I. INTRODUCTION

We report system parameters measured on a 23-mile, atmospheric, optical-transmission path. The object of the investigation is to determine whether a modulated optical signal transmitted through the atmosphere could be used as a stand-by substitute for a microwave radio link when transmission over the radio path is impaired by clear-air multipath or obstruction fading.

So far, we have learned that:

(*i*) The control of the transmitter elevation angle can be accomplished with an error signal from the receiver. This compensates for atmospheric refractive index gradient changes, which change the curvature of the optical beam.

(*ii*) There is very little need for horizontal beam correction.

(*iii*) The transmitter can be scanned up and down when severe path loss has attenuated the signal below the detection level so as to reestablish the link after the path loss is reduced.

(*iv*) The clear-air path loss is 27 dB. Of this, 17 dB is due to scattering and 10 dB is due to the receiver intercepting only 10 percent of the beam.

(*v*) The received beam is 20 feet in diameter where the received signal is 10 dB below its value at the beam center and 32 feet in diameter where the signal is down 20 dB.

(*vi*) The calculated clear-air peak-signal-to-average-noise ratio, including the background light, is between 57 and 63 dB, using a 20-mW laser.

It has been determined[1] that rain and fog can cause as much as 0.1-dB/ft optical-transmission loss, and, at such times, optical transmission on a 20- to 30-mile path is very difficult. However, it is believed that most microwave multipath fading occurs in relatively clear weather, and to date, our measurements have shown this to be true. Thus, when microwave clear-air fading occurs, the attenuation of the optical signal should be low.[2] Recently, Schiavone[3] has shown that 7 percent of the 30-dB clear-air microwave fade-time at Palmetto, Georgia, occurs jointly with visibilities of 4 miles or less. The remaining 93 percent occurs during times of better visibility.

Further, because of the very narrow beam that can be obtained with light,* there should be no multipath fading of the optical signal.* Again, our limited measurements to date have shown no multipath fading at optical frequencies while multipath fading was occurring at 11 GHz.

II. LOCATION OF THE EXPERIMENT

Figure 1 shows the location of the experiment and also a vertical profile of the path. About three miles of the 23-mile path are over tidal water.

The transmitter is mounted in a cab at the top of a 100-foot steel tower at Murray Hill. The tower is shown in Fig. 2. The optical beam

* For a 1-foot antenna, at 6328Å, the ratio, D/λ, is 4.8×10^5, whereas for a 6-foot antenna at 4 GHz, D/λ is 2.4×10^1. This results in a 3-dB width at the receiver of 0.25 feet for the optical beam and 4800 feet for the 4-GHz beam.

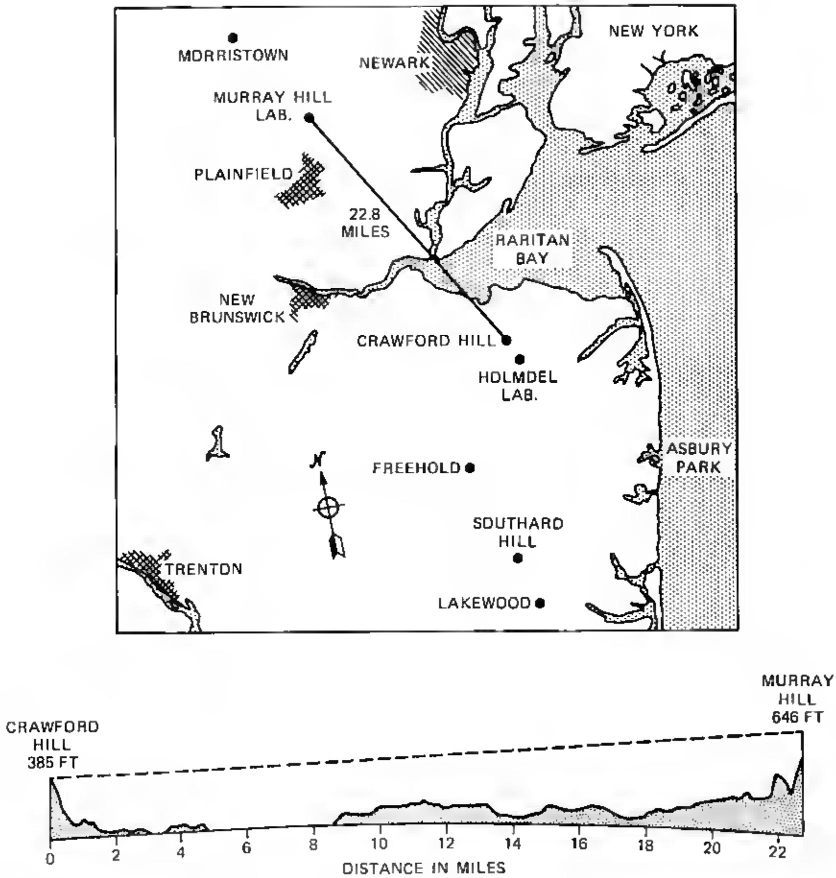

Fig. 1—Map and profile of the transmission path.

is transmitted through the cylinder protruding from the flat surface at the top of the tower. Two microwave antennas on the tower are used to measure multipath fading on the same path (11 and 30 GHz).

The optical receiver at Crawford Hill is shown in Fig. 3. The two microwave antennas on the left of the photograph are part of the microwave multipath-fading experiment.

III. THE TRANSMITTER

Figures 4 and 5 show a diagram and a photograph of the transmitter, respectively. It is composed of a rigid but movable telescope framework, 10-feet long and 1-1/2-feet wide and high, mounted at one end on an orthogonal pair of gimbals and supported on a fulcrum at the other. The telescope gimbals are mounted on one end of a rigid *L*-shaped base, while the other end of the base provides a mount for a

Fig. 2—Transmitter tower at Murray Hill.

second fulcrum. The fulcrum of the telescope and that of the base are about three inches apart. A steel lever pivots on the stationary fulcrum of the base and supports the fulcrum of the telescope. The length of the lever is such that a one-mil (0.001-inch) movement at its free end ("A") causes the telescope to move 0.46 μrad, or a beam motion of about 6.4 feet at the receiver. The lever and fulcrum allow both vertical and horizontal adjustments of the telescope direction.

The position of the free end of the lever is controlled by two small motors. Two tones (900 and 1100 Hz), delivered over a pair of telephone lines from the receiver, control the vertical and horizontal position of the transmitter telescope. The response is relatively slow; a one-second burst of one of the tones moves the optical beam 13.5 inches at the receiver 23 miles away (9.3 μrad/s).

The laser power is 15 mW at 6328Å. The beam is modulated by a chopper wheel, which produces 450 pulses per second, with equal off and on time. To derive a synchronizing signal, light reflected from the chopper is detected and the 450-Hz tone is transmitted over a third

Fig. 3—Receiver assembly at Crawford Hill.

telephone line to the receiver. There, the tone is used to phase-lock the local oscillators of the homodyne detectors.

The rays of the optical signal at the transmitter are shown in Fig. 4. The focal point of the 12-inch mirror is made to fall, by the angle (45 degrees) and position of the small (2-inch diameter) plane mirror inside the telescope, just outside the top of the telescope. To allow sighting through this transmitting telescope for alignment on the receiver, the beam is collimated with a 10-diopter lens. A prism inserted just above this lens bends the beam outward, and allows precise alignment by eye. When used as a transmitter, the collimated beam is focused by a second 10-diopter lens at the focus of a 10-power microscope objective.

IV. THE RECEIVER

The configuration of optical receiving antennas is shown in the photograph of Fig. 3 and the sketch of Fig. 6. Each element is composed of a 24- × 18-inch plastic Fresnel lens mounted in a weathertight, sheet-metal cone, with a photomultiplier at the focus. To reduce background noise, the optical signal passes through a 6328Å filter. This filter reduces the background current 22 dB and the signal 3 dB, for a net 19-dB improvement. In addition, the aperture (0.5 inch) of the photomultiplier is reduced to 0.1 inch with an iris. This reduces the background current 14 dB. Finally, to narrow the part of the sky seen by the photomultiplier, a rectangular bundle of thirty rectangular

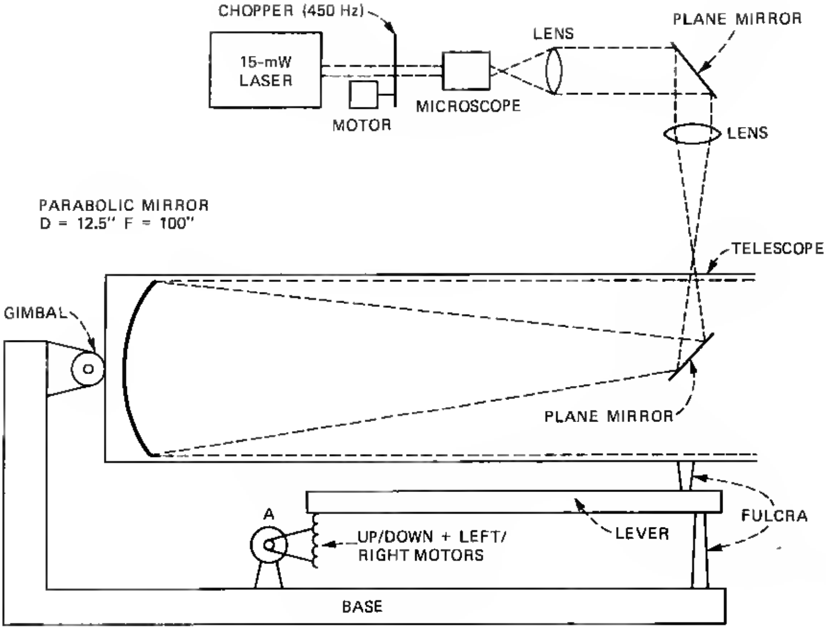

Fig. 4—A diagram of the transmitter.

(4 × 4 inches) tubes is mounted in front of the Fresnel lens. This reduces the background current 4 dB. There are four optical antennas in the receiver mount.

As we see in Fig. 7, the 450-Hz signals from the four photomultipliers are passed through an automatic gain control (AGC) step attenuator (0 to 40 dB in four steps of 10 dB). Each of the four signals is then amplified and band-limited in a homodyne detector. The output signals of the four homodyne detectors are indicated as A, B, C, and D in Fig. 7. These outputs are dc voltages linearly proportional to the power of the incoming 450-Hz optical signal. An input signal of 100 μV rms to each homodyne detector produces 10V dc at its output.

The four signals, A, B, C, and D in Fig. 7, are combined in a summing amplifier to give an indication of the optical signal strength and the integrated sum is recorded on a chart recorder. The sum is also used to control the AGC and to put the system into a search mode when the sum signal falls below a fixed threshold.

The four signals, A, B, C, and D in Fig. 7, are used to control the elevation angle of the transmitter. The signals A and B from the top two antennas are added, as are the signals C and D from the bottom. The sum A plus B is subtracted from the sum C plus D in a comparator. If the difference is positive, the lower half of the receiver is receiving a stronger signal, and if the difference exceeds a threshold, an 1100-Hz

Fig. 5—Transmitter assembly.

tone is applied to the phone line. This tone causes the transmitter to elevate the beam-launch angle. A negative difference causes a 900-Hz tone, which lowers the beam-launch angle. In this way, the transmitter keeps the beam centered on the receiver.

The search control is designed to bring the optical beam back onto the receiver after a deep fade of the optical signal. The search control goes into action when:

(*i*) The sum signal falls below a threshold, and also

(*ii*) All of the attenuators are out of the AGC (zero AGC loss).

In the search mode, a sequence of 200 up commands (1100 Hz) (1 second on, 6 seconds off) is followed by a similar sequence of 200 down commands (900 Hz).* To assure that the search control is in sole command, when it is in operation the up/down servo is disabled. This vertical scanning continues until the sum signal exceeds a threshold, at which time control is handed off to the vertical servo controller. All but one of the thresholds are compared with the sum voltage ($A + B + C + D$). Figure 8 shows the thresholds and the action taken.

First, the summing amplifier saturates at 9.5 volts, which sets the upper limit. The attenuators are inserted, 10 dB at a time and with a

* Two hundred seconds of command takes the transmitter from top to bottom of its range of motion (1495 μrad at the transmitter or 182 feet vertical motion at the receiver).

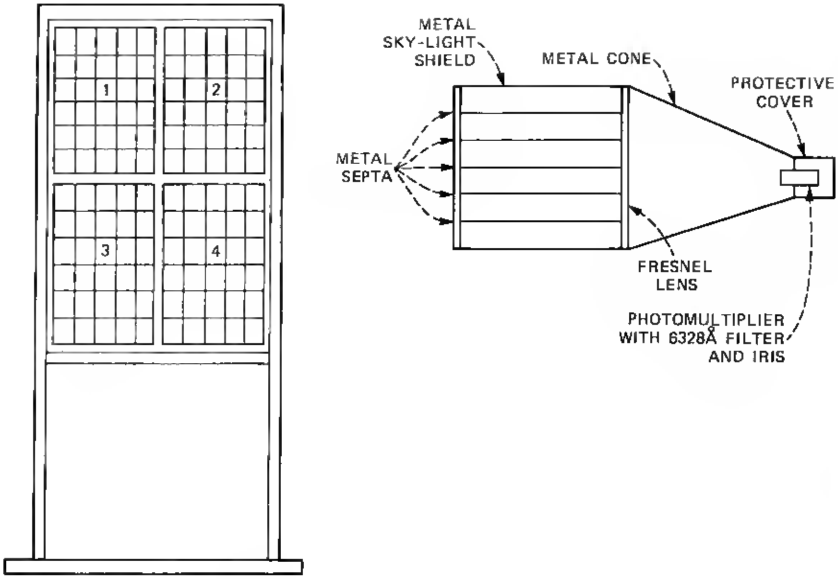

Fig. 6—A diagram of the receiver assembly.

10-second delay between insertions, when the sum voltage is 5 volts or more. The attenuators are taken out, 10 dB at a time and at 10-second intervals, when the sum voltage is 50 millivolts or less. The 100/1 threshold ratio is required to minimize attenuator switching owing to scintillation.

One of the thresholds in Fig. 8 is not compared with the sum voltage but rather with the difference $(A + B)-(C + D)$. This difference voltage is the up/down servo command and the minimum threshold is 20 mV. As the sum voltage increases, part of the sum is used to increase this threshold, which minimizes rapid hunting at high signal levels.

The last pair of thresholds turns the search control on and off. The search is turned on when the sum voltage is less than 200 mV and off when it exceeds 500 mV. These rather high thresholds are determined by the clear-air off-axis signal of 150 mV. It was found that, in very clear weather, when the transmitter was moved as far as it could be off the receiver, there was still a sum signal of 150 mV.

V. THE BEAM

5.1 Received beam diameter

The shape of the optical beam at the receiver was determined by incrementally scanning the transmitter and recording the received signal. The distance of motion of the lever in the transmitter (A in Fig.

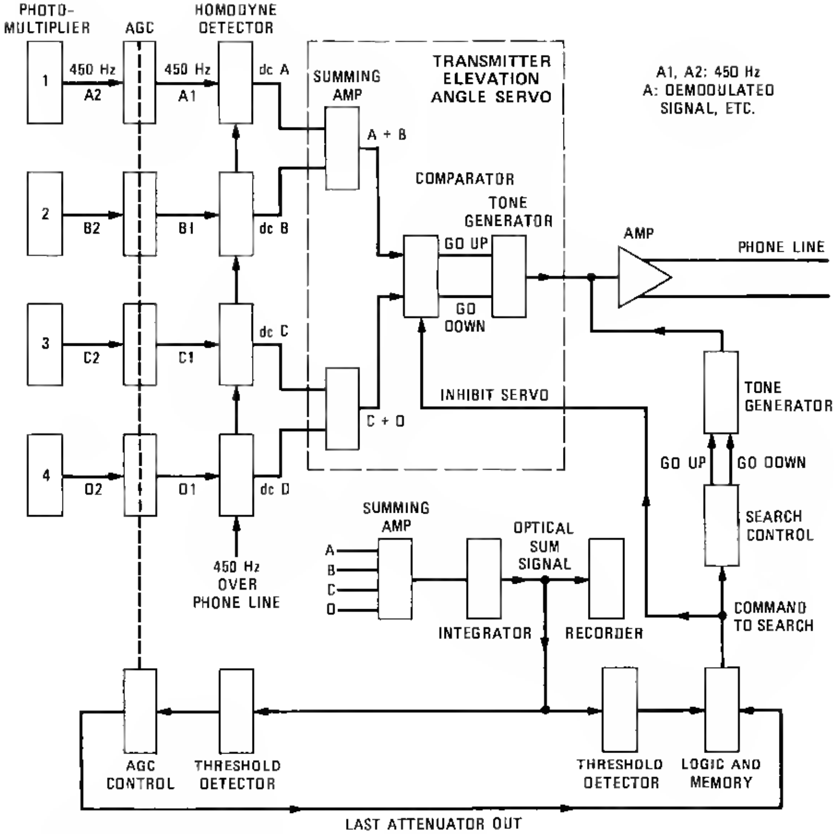

Fig. 7—An electrical diagram of the receiver.

4) was measured and converted to feet of optical-beam motion at the receiver (0.46 μradians of beam motion for each 0.001-inch motion at A). This is the abscissa in Fig. 9. The ordinate is simply the sum voltage converted to dB. At the 10-dB point, the beam is about 20 feet in diameter, and at 20 dB, the beam is about 30 feet in diameter.

5.2 Path loss

The receiving antenna is about 3 × 4 feet, and the beam decreases only about 0.5 dB over this area. If all of the power at the receiver is assumed to lie within a 32-foot diameter circle (signal down 20 dB), and the power distribution over this area is calculated using the data of Fig. 9, the power into the 12-square-foot receiver is down about 10 dB below the total power. So, what might be considered the geometric efficiency, that is to say, the fraction of the total optical power in the beam at the receiver that is intercepted by the receiver, is 10 percent.

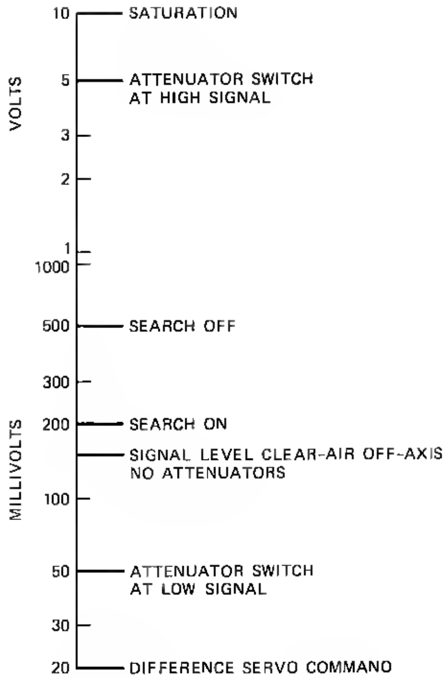

Fig. 8—Optical-system-control voltage levels.

However, there is another source of loss. Energy is scattered by the atmosphere. To determine the amount of this loss, the signal was measured at the end of the transmitter telescope, using a Fresnel lens and photomultiplier identical to those at the receiver. Twenty-seven dB of optical attenuation were inserted in the narrow collimated beam between the two 10-diopter lenses (at the transmitter) to bring the measured signal to the value observed at the receiver. Thus, we conclude that the scattering causes some 17 dB of path loss, and the total path loss, using four receiving antennas, is 27 dB. The *Handbook of Optics* indicates a 16-dB loss on a 23-mile path.[4]

5.3 Vertical beam motion

The transmitter is capable of 1495 μrad of vertical motion. This was consistent with the beam movement measured by Ochs and Lawrence,[5] who reported a maximum of 1023 μrad of vertical motion on a 28-mile path. The path from Murray Hill to Crawford Hill is 23 miles. This 1495 μrad of vertical motion has been found to be adequate to compensate for atmospheric changes on this path. Figure 10a shows a typical early-morning decrease of the transmitter elevation angle. The movement is 478 μrad at a 0.07-μrad/s rate. The largest early-morning

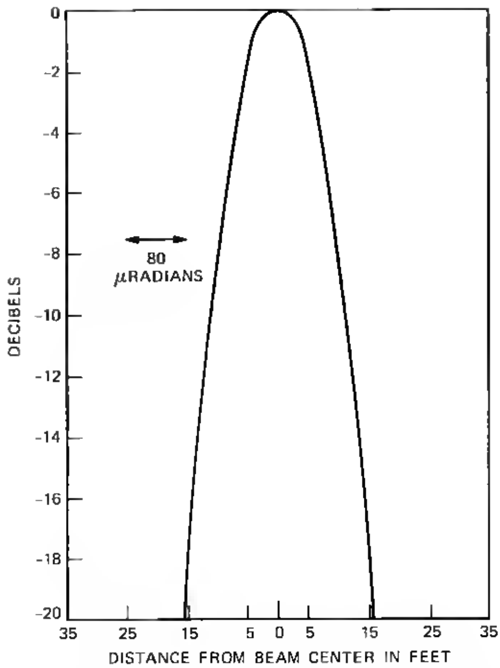

Fig. 9—Optical beam power vs distance from beam center.

movement recorded is shown in Fig. 10b. Here the transmitter moved 990 μrad at a rate of 0.18 μrad/s. The fastest transmitter movement observed was 0.89 μrad/s, well below the 9.3-μrad/s capability of the system. Ochs and Lawrence show a rate of 0.12 μrad/s on a 28-mile path.

The operation of the search control is shown in Fig. 10c. A heavy rainstorm brought the signal below the control threshold at about 16:20 and the transmitter began to search. It takes 39 minutes to complete an up/down scan. At 20:50 the signal was strong enough to turn off the search control, and the system returned to normal operation.

5.4 Attenuator operation

Fog and rain can attenuate the optical signal severely. It was found that the up/down servo control was operable when the signal had faded 40 dB below its clear-air value. To keep the control voltages within a reasonable range, an AGC was used, and is shown in Fig. 7. When the sum-signal exceeds 5 volts a 10-dB attenuator is switched into the signal path, and when it falls below 50 mV a 10-dB attenuator is removed. Figure 11 shows a signal fade which, at 17:25, caused a 10-dB attenuator to be removed.

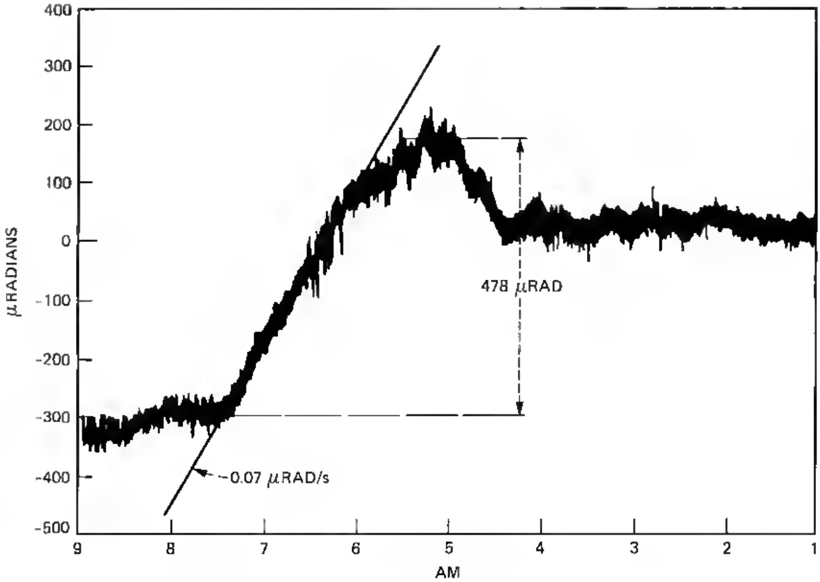

Fig. 10a—Transmitter elevation angle vs time (sunrise).

5.5 Beam microstructure

In addition to the effect of fog and rain, which causes the optical signal to be attenuated by about the same amount for all the receiving antennas, there is fine structure in the path, which causes small variations of the signal in each of the four antennas.[6] A measurement of this phenomenon is shown in Fig. 12a, which shows the output signal of the homodyne detectors with a 6-dB/octave, 0.1-second, time-constant output filter.

Small cells of heated and cooled air cause the velocity of the light to change slightly and differently in each ray. At the receiver, the signal is brighter where the preponderance of rays reaching the antenna are in phase, and dimmer where some of the rays to the antenna are out of phase with the remainder.

Ochs[6] reports that the delayed correlation between horizontal detectors is used to measure wind velocity. If this is done with the data of Fig. 12a, there is about a 0.1-second delay, left to right, in a distance of some 18 inches. This indicates a 10-mph east to west component of wind.

The photomultiplier in Antenna 1, which is seen in Figure 12a, was about 2 to 3 dB less sensitive than the other three. The signal from any one antenna shown in Fig. 12a varies as much as 5 dB in the 2.4-second record, and shows a maximum rate of change of about 18 dB/s. In Fig. 12b, the sums of the top $(A + B)$ and bottom $(C + D)$

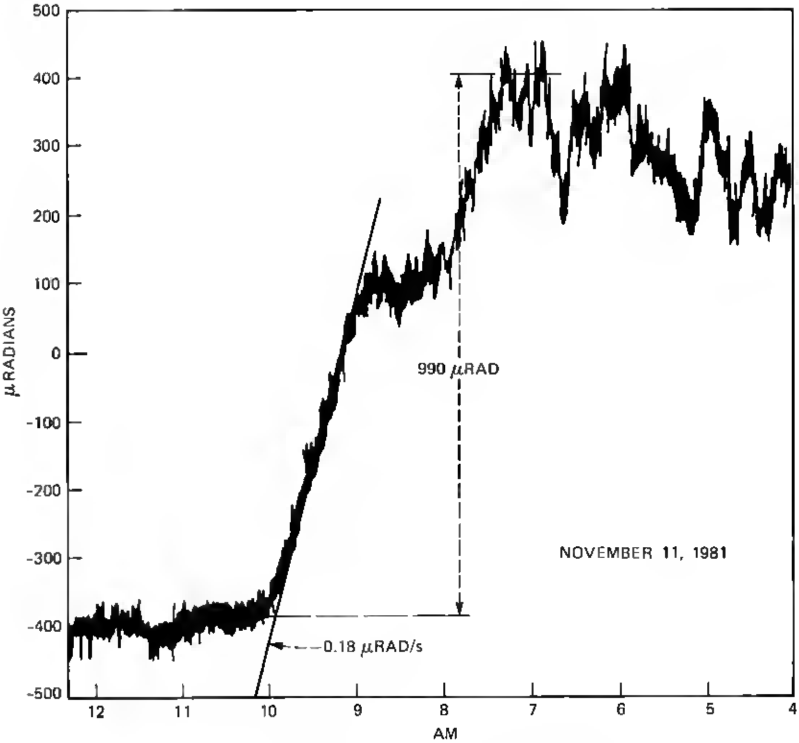

Fig. 10b—Transmitter elevation angle vs time (sunrise).

antennas are shown. At 0.5 second, the up/down servo would command the transmitter to go up, at 1.3 seconds to go down, and at 2 seconds to go up. It is to be observed that the two sums do not change as much (about 3 dB) nor as rapidly (about 11 dB/s) as the separate signals. Finally, the sum of all four signals is shown in Fig. 12c. The sum signal changes about 2 dB with a maximum rate of change of 7 dB/s. It is clear that increasing the size of the receiving antenna reduces the magnitude and rate of rapid signal fluctuations.

5.6 Scintillation

The gross effect of beam microstructure on the sum signal is usually called scintillation. Scintillation is present in microwave radio signals, and is known to increase with frequency, all other things being equal. As was shown in Section 5.5, the optical scintillation decreased with increasing antenna area. Because of the large optical antennas the scintillation measured on the optical path is no worse than that measured on the parallel 30-GHz path, though larger than that on the parallel 11-GHz path. Hannan et al.[7] report optical scintillation as severe as 10 dB.

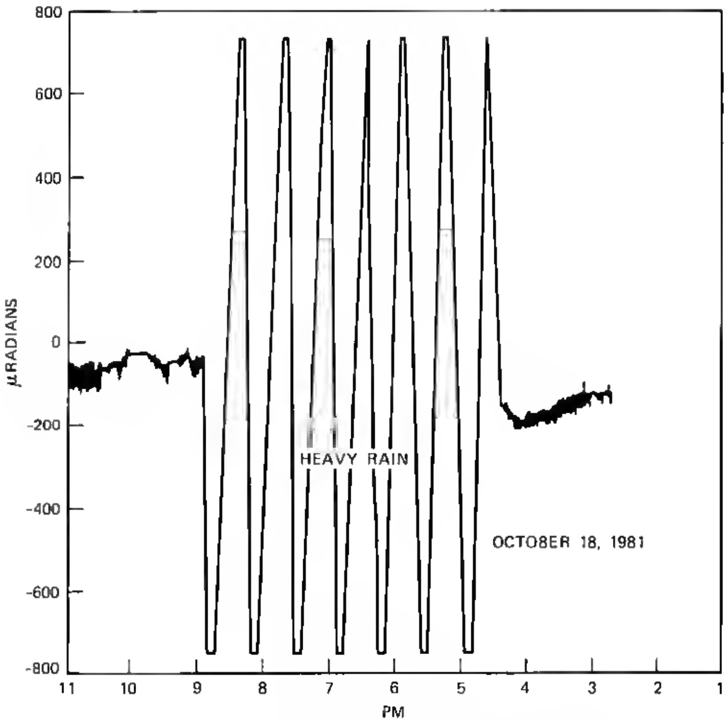

Fig. 10c—Transmitter elevation angle vs time (search mode).

Figure 13 shows the 450-Hz modulation signal, obtained directly from one of the photomultipliers on a clear, cool, sunny day. In Fig. 13a the maximum signal is about 500 mV (across 10 kilohms) and the minimum about 380 mV, a ratio of about a 1.2 dB. Of interest here is the structure seen at the maximum of the negative-going signal. It is clear that even with this large antenna the beam microstructure has components above one kilohertz. In Fig. 13b, taken at a ten times slower rate, the maximum signal is about 500 mV and the minimum about 180, a change of 4 dB. There are several instances where the rate of change is very rapid. For example, the signal drops from 450 mV to 300 mV in two pulses, or a change of 1.8 dB in 4.4 ms (or about 400 dB/s).

5.7 Optical signal during an 11-GHz multipath fade

Figure 14a shows an 11-GHz, clear-air, multipath-fading and enhancement event. The fading is frequency selective with a maximum slope of about 2 dB over the 40-MHz band.

Figure 14b shows the same event along with the optical signal. The normal, clear-air signal level of the 11-GHz event was 2 volts. There is

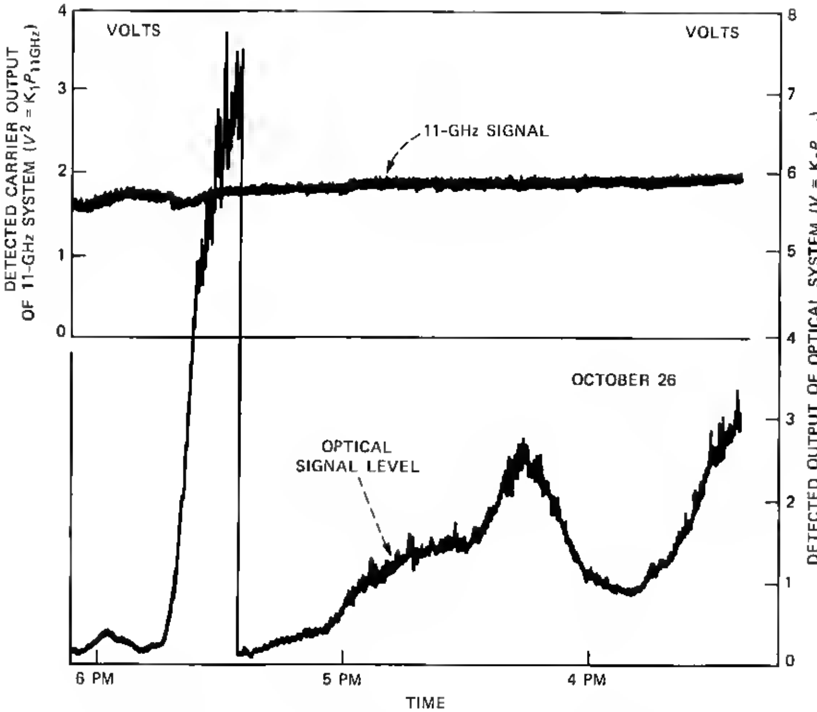

Fig. 11—Microwave and optical signal vs time (attenuator removed).

almost 6 dB of enhancement and about 12 dB of fading. The optical signal shows no fading and very little scintillation.

VI. NOISE

In the preceding sections it has been shown that a beam of light can be transmitted 23 miles. By using feedback from the receiver to control the transmitter elevation angle, the rather narrow beam (2.4×10^{-4} radians between -20 dB levels) can be kept centered on the receiver. And finally, by scanning the transmitter vertically, transmitter elevation control can be reestablished after a deep fade.

There is still the question of the ability of the optical system to satisfactorily carry information at the rates necessary. As is shown in the appendix, there are modulators available that will impress the information of a microwave intermediate frequency (IF) signal onto the light beam. The remaining question is, can the signal be received with sufficient accuracy to provide a satisfactory replica of the impressed signal?

The photomultipliers are fast enough for either frequency modulation (FM) or pulse code modulation (PCM), having a 3-ns rise time. If

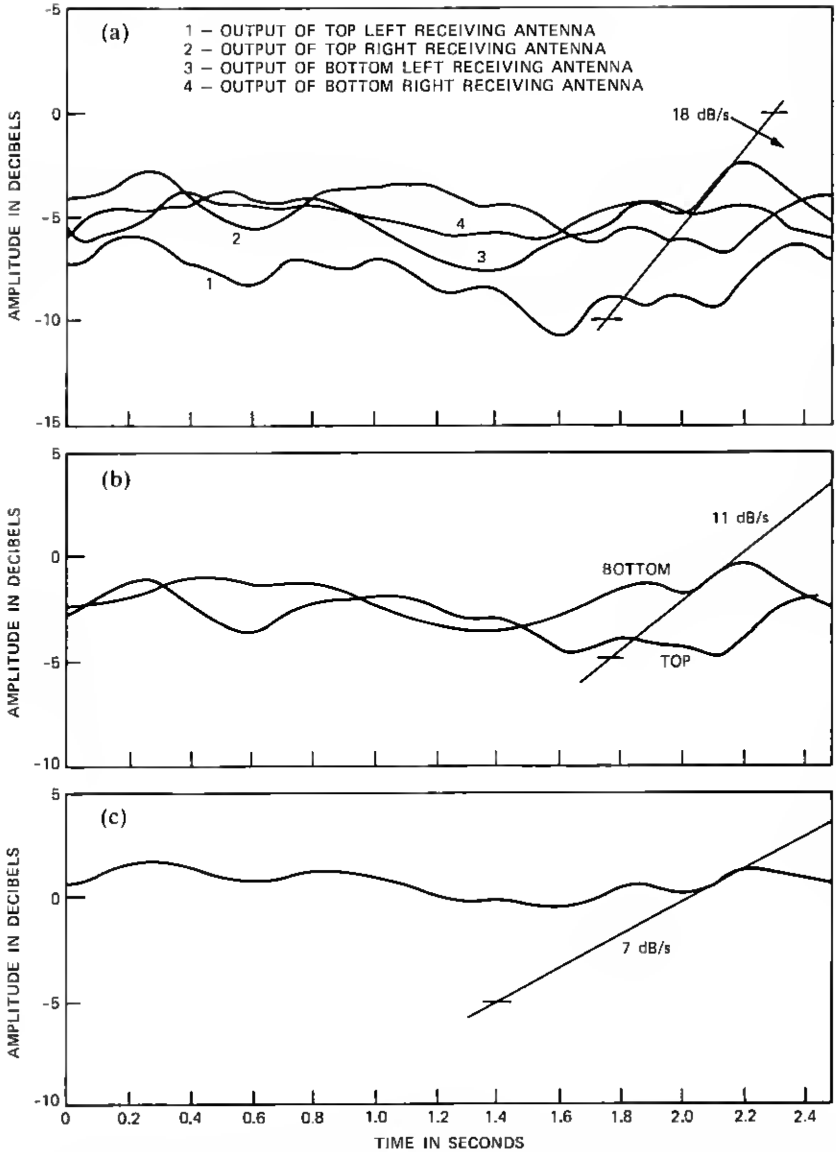

Fig. 12—(a) Demodulated output of four individual photomultipliers vs time. (b) Demodulated output of upper and lower photomultiplier pairs vs time. (c) Demodulated output of sum signal of four photomultipliers vs time.

the 4-MHz baseband signal is sampled at 8 MHz and encoded into 8-bit PCM,*[8] the rate is only 64 MHz. This is well within the 100-MHz capability of the modulator and photomultiplier. In a commercial

* Because noise is spread over the entire band, 8-bit PCM is adequate.

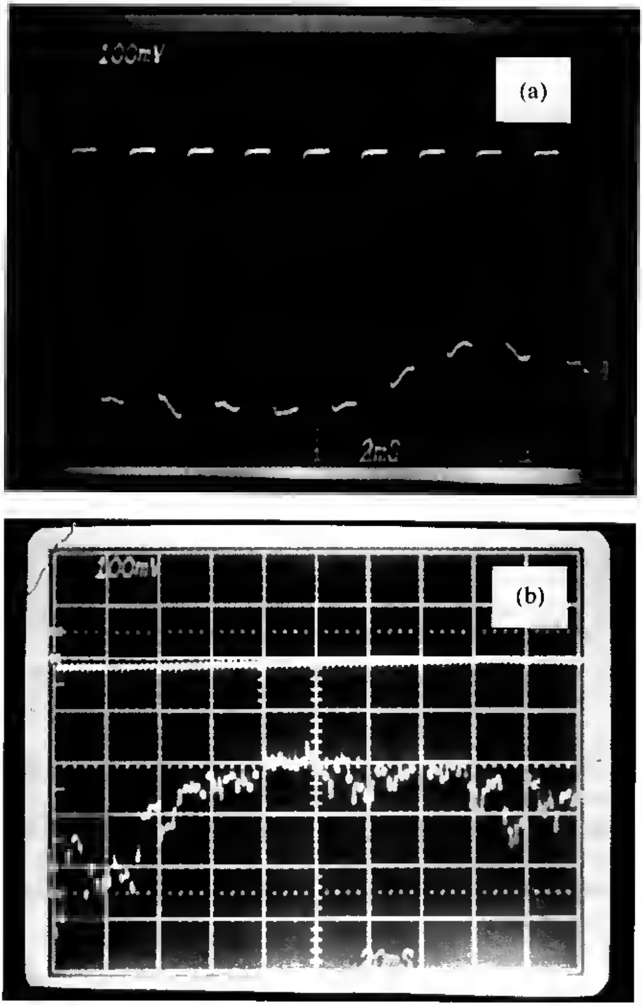

Fig. 13—(a) The ac of one photomultiplier vs time (2 ms/div). (b) The ac of one photomultiplier vs time (20 ms/div).

system, the photomultipliers would almost certainly be replaced with p-i-n diodes, and they are even faster.

So the only question is the noise generated in the receiver. There are four sources of noise in an atmospheric receiver:

(*i*) Thermal noise
(*ii*) Shot noise of the signal current
(*iii*) Shot noise of the current because of background illumination
(*iv*) Shot noise of the dark current.

The thermal noise has a mean-square value of

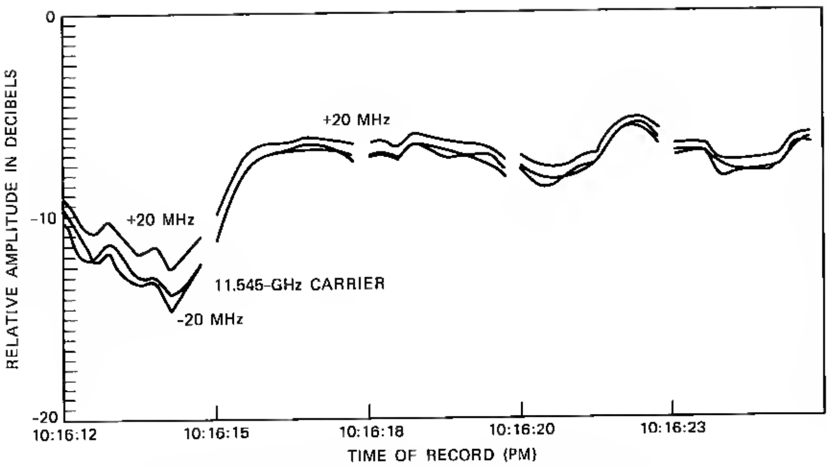

Fig. 14a—Detected amplitude of 11-GHz tones vs time.

$$\overline{i^2} = \frac{4KTB}{R},$$

where K is Boltzman's constant (1.38×10^{-23}), T is temperature (300°K), B is the bandwidth (10^8 Hz), and R is the amplifier input resistance.

The thermal noise can be made very small by using a transimpedance amplifier. But we will calculate the noise using an input resistance ranging from 50 to 1000Ω, which with the interelectrode capacitance of 3 pF gives a time constant 0.15 to 3 ns.

The average current squared ($\overline{i_{\text{sig}}^2}$) of the shot noise of the signal current (I_{sig}) is simply

$$\overline{i_{\text{sig}}^2} = 2e\,\frac{I_{\text{sig}}}{2}\,B,$$

where e is the electron charge (1.6×10^{-19}) coulombs.

The noise owing to the background illumination is

$$\overline{I_{\text{back}}^2} = 2eI_{\text{back}}B,$$

where I_{back} is the dc current due to background illumination.

By the use of the hood in front of the Fresnel lens and the iris and red filter at the photomultiplier, the background illumination, under the worst condition, causes three times as much current as the average signal current if the anode voltage is limited to 800 volts (maximum anode voltage is 1500). Therefore, $I_{\text{back max}} = 3\, I_{\text{sig}}/2$. Most of the time, the two currents are about equal (i.e., $I_{\text{back}} = I_{\text{sig}}/2$). Of course, at night, there is virtually no background current. The peak signal current is

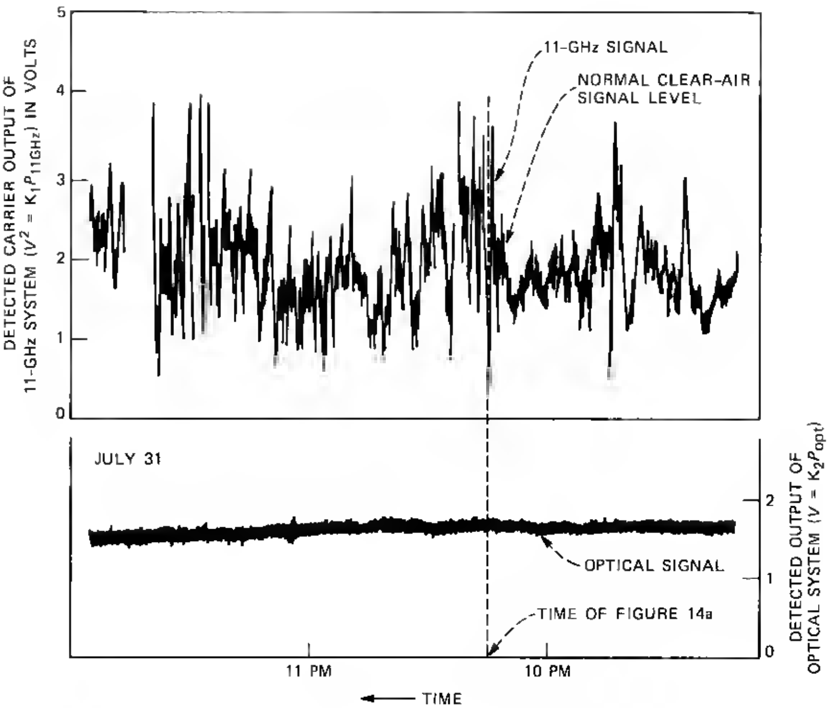

Fig. 14b—Detected amplitude of 11-GHz carrier and optical signal vs time.

about 50 μA and the highest background current was 75 μA. The dark current is three orders of magnitude smaller than the signal current, and can be ignored.

A useful measure of a receiver is the signal-to-noise ratio, and we can calculate it for this receiver with the information we have.

Figure 13b shows the output of one photomultiplier on a typical day. The voltage across a 10-kilohm resistor varies between 500 mV and 175 mV. The average, without scintillation, is 340 mV or a current of 34 μA, and from the four antennas the average sum is 136 μA. The background current was about equal to the average signal current at the time of the measurement. The peak-signal-to-average-noise ratio for an on/off PCM signal can be written as

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{(I_{\mathrm{sig}})^2}{2\mathrm{e}\left(\frac{1}{2}\,I_{\mathrm{sig}}\right)B\left(1 + \frac{2I_{\mathrm{back}}}{I_{\mathrm{sig}}}\right) + \frac{4\mathrm{K}TB}{R}}.$$

The calculated peak-signal-to-average-noise ratio S/N, using an average signal current of 136 μA, is shown in Table I.

Scintillation can cause a considerable variation of received signal. It

Table I—Calculated peak-signal-to-average-noise ratio

$I_{back}/I_{sig\ avg}$	R (Ω)	Signal to noise (dB)
0	50	58
0	100	60
0	1000	67
1	50	57
1	100	60
1	1000	65
3	50	57
3	100	59
3	1000	63

usually amounts to plus or minus several decibels. Under severe conditions it has been seen to cause ±10 dB variation of received signal.[7]

VII. CONCLUSIONS

We have shown that:

(*i*) The elevation angle of an optical transmitter must be continuously adjusted to compensate for beam-curvature changes in the atmosphere, and that this can be done by a servo signal from the receiver.

(*ii*) The azimuth angle of an optical transmitter need not be corrected on a continuous basis. Occasional manual adjustment (every month or so) is adequate.

(*iii*) Heavy fog or rain will cause a total loss of optical signal, but the optical system can be reestablished by scanning the transmitter vertically.

(*iv*) The clear-air path loss is 27 dB on a 23-mile path.

(*v*) The received beam diameter is 32 feet, where the power is 20 dB below the level at the center of the beam.

(*vi*) The sky light can cause as much as three times as much current in the receiver as the average signal current, and this gives a system peak-signal-to-average-noise ratio of about 60 dB.

(*vii*) Modulators exist that should comfortably accommodate either the microwave IF signal (centered at 70 MHz) or a digitized version of the 4-MHz baseband.

(*viii*) The received signal scintillates several decibels most of the time, and can get as severe as 10 dB. The frequency rate of scintillation contains components up to several kilohertz.

(*ix*) During a clear-air microwave fade, the optical signal did not fade, and in fact, had much less scintillation than usual.

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APPENDIX

Modulation of Light

There are two well-developed optical-modulation techniques. Both involve transparent solids that allow an electrical signal applied to the solid to modify the transmission of light through the solid. In one, the transparent body is mechanically driven by a piezoelectric driver and the pressure standing-wave is employed to form an optical diffraction grating in the body of the solid. This grating causes part of the light to be bent out of its unmodified path and this deflected part of the beam is used as the modulated optical signal. The frequency of the signal that causes this grating is relatively high, on the order of 100 MHz, and is resonant in the crystal. Digital or analogue modulation is impressed on the light beam by either keying the high-frequency signal off and on or linearly modulating its magnitude. Because of the time required for the resonance to build up and to decay, the modulating signal is usually much smaller than the resonant frequency, on the order of a few megabits or megacycles.

The other type of modulator uses a crystal in which the polarization angle of the light is rotated by the electrical signal. The crystal tends to be square in cross section (about 1/2 mm on a side) and about 1 cm long. Metal is plated onto two opposite long surfaces, and the signal voltage is applied to these. The light is passed through the long axis of the crystal in a path parallel to the plated surfaces. The light coming out of the crystal has some polarization, and is passed through a polarizer plate with its surface normal to the optical beam.

When voltage is applied, the polarization of the light out of the crystal rotates in proportion to the voltage applied, and after passing through the output polarizer, the output optical power is changed. The process is continuous, that is to say, the light can be brought back to the original polarization by applying enough voltage. The power out of the output polarizer varies as

$$P_{out} = K_1 P_{in} \sin^2 K_2 V_{in}, \tag{1}$$

where K_1 is the maximum through-transmission, $K_2 = 2\pi/V_{360}$, and V_{360} is the voltage needed to cause 360° of phase rotation. If the voltage applied is a sinewave $V_{in} = V_0 \sin \omega t$, and the crystal is biased with a dc voltage, V_B, then the output power is

$$\begin{aligned} P_{out} &= K_1 P_{in} \sin^2(K_2 V_B + K_2 V_0 \sin \omega t) \\ &= \frac{K_1 P_{in}}{2} [1 - \cos 2(K_2 V_B + K_2 V_0 \sin \omega t)] \\ &= \frac{K_1 P_{in}}{2} [1 - \cos(2K_2 V_B)\cos(2K_2 V_0 \sin \omega t) \\ &\qquad + \sin(2K_2 V_B)\sin(2K_2 V_0 \sin \omega t)]. \end{aligned} \tag{2}$$

It is well known that

$$\cos(a \sin\theta) = J_0(a) + 2J_2(a)\cos 2\theta + 2J_4(a)\cos 4\theta + \cdots$$

and

$$\sin(a \sin\theta) = 2J_1(a)\sin\theta + 2J_3(a)\sin 3\theta + 2J_5(a)\sin 5\theta + \cdots.$$

Let $2K_2 V_B = b$ and $2K_2 V_0 = a$. Then

$$\begin{aligned} P_{out} = \frac{K_1 P_{in}}{2} \{1 - \cos b[J_0(a) + 2J_2(a)\cos 2\omega t + \cdots] \\ + \sin b[2J_1(a)\sin \omega t + 2J_3(a)\sin 3\omega t + \cdots]\}. \end{aligned} \tag{3}$$

To avoid all even harmonics, set $b = \pi/2$

$$\begin{aligned} b = 2K_2 V_B &= \frac{\pi}{2} = 2 \frac{2\pi}{V_{360}} V_B \\ V_B &= \frac{V_{360}}{8}. \end{aligned} \tag{4}$$

With this bias, only the fundamental and its odd harmonics are present in the modulated signal.

The fraction of the optical power going into the harmonics is determined by the amplitude of the impressed signal, V_0. The argument of the Bessel functions is

$$a = \frac{\pi}{2} \frac{V_0}{V_B}. \tag{5}$$

Because of the nonlinearity of the modulator there is a relatively strong (−27 dB) third harmonic at only 20-percent modulation of the fundamental $[m = 2J_1(4\pi V_0/V_{360})]$.

However, such nonlinearity has little effect on an FM signal so long as the amplitude of the FM signal is constant. The fundamental and its sidebands can be filtered from the higher harmonics, and with no

second harmonic present, this is easily done with a microwave intermediate frequency (IF) signal. If the IF signal is centered at 70 MHz, the deviation is ±4 MHz and the baseband signal bandwidth is 4 MHz. The highest sideband of the fundamental, using Carson's rule, is $f_c + \Delta f + f_B = 70 + 8 + 4 = 82$ MHz. The lowest sideband of the third harmonic is $3f_c - 3\Delta f - f_B = 210 - 24 - 4 = 182$ MHz. This should be easily taken care of by the filter in a microwave receiver.

All of the above assumes that the modulation is FM. This requires that the bias be set at $V_{360}/8$. However, binary PCM transmission calls for setting the bias so that no light is transmitted when the signal is a zero and maximum light is transmitted when the signal is a one. Thus, for PCM the bias V_B is set at zero and the digital signal "one" is set at $V_B = V_{360}/4$. The harmonic generation during the transition is of little concern.

Acousto-optic and electro-optic modulators are commercially available. The acousto-optic modulators allow modulation up to about 3.5 MHz with rise and fall times of 120 ns, which is inadequate for most microwave IF signals. The modulation efficiency is about 85 percent, and the extinction ratio is about 1000:1. The electro-optic modulators allow modulation up to 100 MHz with rise and fall times of 3.5 ns. The depth of modulation at 6328Å is 85 percent and the extinction ratio is 500:1. The electro-optic modulators require a feedback bias control.